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14. ABSTRACT
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Thermal Conditioning of the AEOS Telescope*

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ABSTRACT

The AEOS telescope facility was designed for high angular resolution imagery. Part of that design is the inclusion of several air handling systems to maximize dome seeing. Four air conditioning units chill the telescope and dome air to the predicted nighttime temperature. There is a mirror purge system, which prevents moisture from condensing on the mirror by blowing desiccated air into the mirror cell. A laminar air system counteracts the seeing degradation effects of a warm mirror by blowing air across the face of the primary. An hour before sunset the dome is partially opened and outside air is pulled through the telescope truss structure in an effort to remove any thermal differences caused by incorrect cooling. Finally a fan pulls air through the coudé tube in order to remove rising air cells. We present details of each system and the beginnings of our experiments to determine their efficacy. Finally, lessons learned from the systems on the AEOS telescope are presented.

Keywords: Mirror Seeing, Seeing

1. INTRODUCTION

The AEOS telescope and its sensors were designed primarily for satellite imaging for the U.S. Air Force and other branches of the U.S. government. One of its prime sensors is an adaptive optics system.[1] Adaptive optics performance critically depends on seeing conditions. As such, it is important to ensure that there is as little dome and mirror seeing as possible. Many features of the dome and telescope were designed with this in mind. We are currently in the process of running a series of tests to determine the efficacy of these systems, and how best to operate them.

2. FACILITY

2.1. Atmospheric Sensors

The first part of minimizing seeing is to know what the weather conditions are. To help with this there are three weather stations located at the Maui Space Surveillance System. One is located on the AEOS dome, a second is located on the roof of the main observatory complex and the final station is located on the summit of Haleakala in Haleakala National Park approximately 200 yards away from the observatory. Each station consists of a humidity sensor, a temperature sensor and a wind sensor. The wind sensor reports wind speed and direction. These sensors are primarily used by the telescope operators to determine when inclement weather is approaching the site and that operations should stop. They also provide valuable data to assist in the analysis of the thermal conditioning systems. In addition to the weather stations, there is a temperature and humidity sensor located inside of the AEOS dome. Finally, there are 32 thermocouple temperature sensors mounted on the telescope. Eight of these are mounted on the back side of the primary mirror. The measurements from all these sensors as well as the calculated dew point are displayed in the observatory control room and are recorded for future study.[2]

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*Based on observations made at the Maui Space Surveillance System operated by Detachment 15 of the U.S. Air Force Research Laboratory's Directed Energy Directorate.

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Thermal Conditioning of the AEOS Telescope*

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2.2. Dome

A standard astronomical dome is a major source of bad seeing, as the dome is heated during the day and at night the warm air is trapped inside of the dome. It can only escape through the slit, which the telescope is observing through. The AEOS dome was designed to mitigate this problem. The dome consists of two concentric cylinders with an aperture at the top. For operations this aperture opens and the dome walls lower, until the telescope emerges from the aperture. The telescope is then fully exposed to the ambient night atmosphere. With this type of dome any warm air in the dome is quickly dispersed into the ambient air. This should eliminate the major cause of dome seeing that plagues standard dome designs. A down side of this dome design is that since the dome fully retracts, the telescope is not protected from wind buffeting; in high wind situations, the dome walls are left up and the telescope observes through the aperture. This restricts viewing to within 30 degrees of zenith.

2.3. Dome Air Handlers

The dome has four air handlers that produce chilled air. By chilling the dome air before operations start, the temperature difference between the telescope and the outside air can be minimized. Once operations start, these air handlers are turned off, otherwise the air flow from the systems causes turbulence around the telescope.

Originally the dome air handlers were set to 45 degrees Fahrenheit, regardless of the outside temperature. This worked fairly well during summer months, but during the winter months, the ambient air was well below this. This resulted in primary mirror temperatures as much as 10 degrees warmer than the ambient air. Large temperature differences like these have highly detrimental effects on image quality.[3456] One method of counteracting this would be to cool the dome to the ambient temperature at the previous sunset. That would be good, but a more accurate predictive method would be better. Marlow[7] derived a method that predicts the temperature at a given time, based on an empirical correlation found between the ambient air pressure trend and the ambient air temperature trend. This was implemented in the spring of 2001 and has been used ever since. This method has worked fairly well.. One thing limiting the accuracy of the predictions is the accuracy of the barometers measuring the pressure. To rectify this, new barometers have been ordered and will be installed on the three weather stations. The average of the three barometers will be used to predict the temperature.

One problem we discovered was that care must be taken to ensure that the temperature set point is not below the dew point, otherwise condensation can form on and inside the telescope structure. At AEOS, this is prevented by requiring a minimum temperature difference of 5 degrees Fahrenheit between the set point and the dew point. This has prevented any further condensation from forming.

2.4. Primary Purge System

While the telescope is in the stow position, dry air is pumped into the volume between the primary and the mirror cover. This prevents moisture from condensing on the primary, which would attack the optical coating. The air is taken from the dome and then dried by pumping it through a desiccant unit, which heats the air to approximately 90 F. The air is then recooled by a separate air handler. The initial recooling air handler did not have the capacity to return the air to ambient air temperature. It only got to 65 F. This was much warmer than the dome set-point and the mirror was heated by this air, undoubtedly contributing to the mirror seeing problem. A new air handler was installed in April of 2002. This has succeeding in cooling the air to 55 degrees. This is still warmer than the ambient air and further work needs to be done. This will most likely involve controlling the temperature that the desiccant system gets to. Most of the time the air is not so humid that it needs full heat.

2.5. Telescope Conditioning System

The telescope has vents mounted at various points on the yoke, base and mirror cell. When the telescope conditioning system is engaged, air is pulled into these vents and through the structure of the telescope. The fan pulling the air is located on the bottom floor of the telescope building on a separate concrete slab than the telescope. This minimizes the transmission of vibrations from the system to the telescope. The air is exhausted several hundred feet away from the telescope downwind of the prevailing wind direction. By pulling ambient

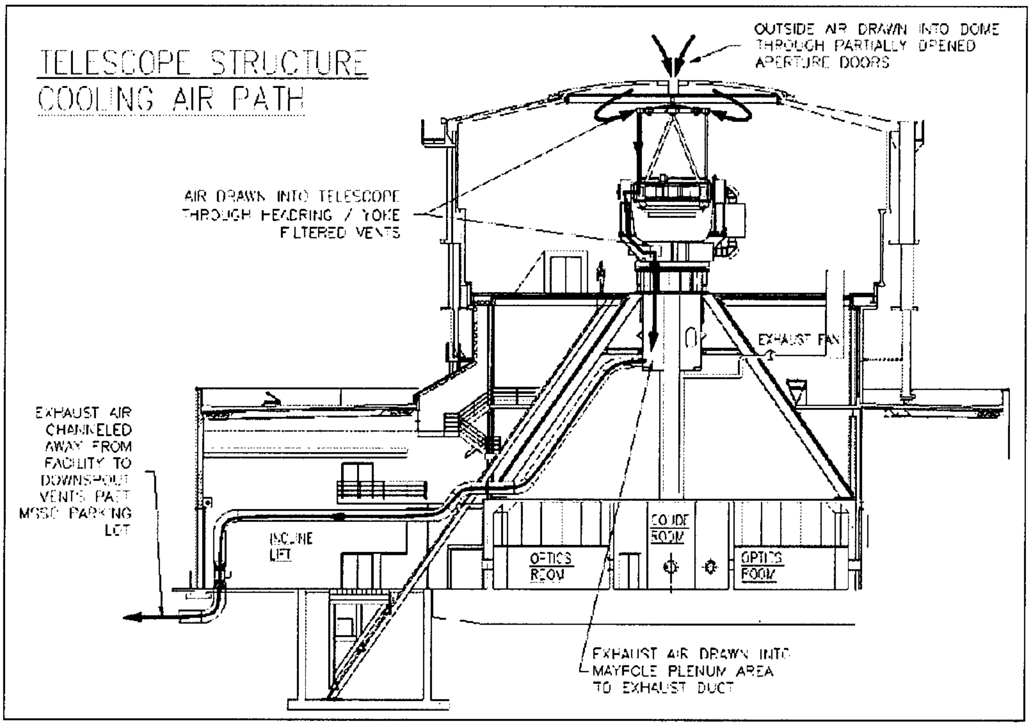

Figure 1. This figure illustrates the telescope conditioning system. On the right hand side of the image is the exhaust fan used by the coudé path conditioning system. The unique dome shape can also be seen in this image. Finally the optical path between the telescope and the optical laboratories can be seen.

air through the telescope, any differences between the temperature of the telescope structure and the ambient air will be eliminated. This is illustrated in Fig. 1.

2.6. Coudé Path Conditioning System

There are seven laboratories in the bottom floor of the AEOS facility, where various experiments can be set up at coudé focus. The light gets from the telescope to these laboratories via a beam tube. The tube is two concentric pipes ending a few inches above an optical window in the ceiling of the central coudé room. A fixed rate fan pulls air down the central pipe and then up the outer tube. The air is exhausted into the dome. The reason why it was returned to the dome and not vented outside is unknown. It probably has little impact on dome seeing, since it is vented over 40 feet from the telescope and it is underneath the retracted dome wall. By the time the air gets near the telescope it will have mixed with a large volume of air. The central coudé room is kept at 62 F, while the temperature of the telescope depends on the season, but it is always cooler than 62 F. The idea behind the fan is that it will eliminate turbulence caused by air rising from the warm room. The experiment rooms and the light path from the telescope to the laboratories is shown in Fig. 1.

2.7. Primary Flushing System

Four fans are mounted on the outside edge of the primary mirror. When engaged, these fans blow air into the volume surrounding the primary, a baffle redirects the air flow across the primary. When the telescope conditioning system is engaged, air is pulled down the central hole in the primary. This air is then exhausted along with the air from the telescope conditioning system. The fans are variable speed, controlled through a rheostat on the fan motor. The primary flushing system is illustrated in Fig. 2. Several previous laboratory

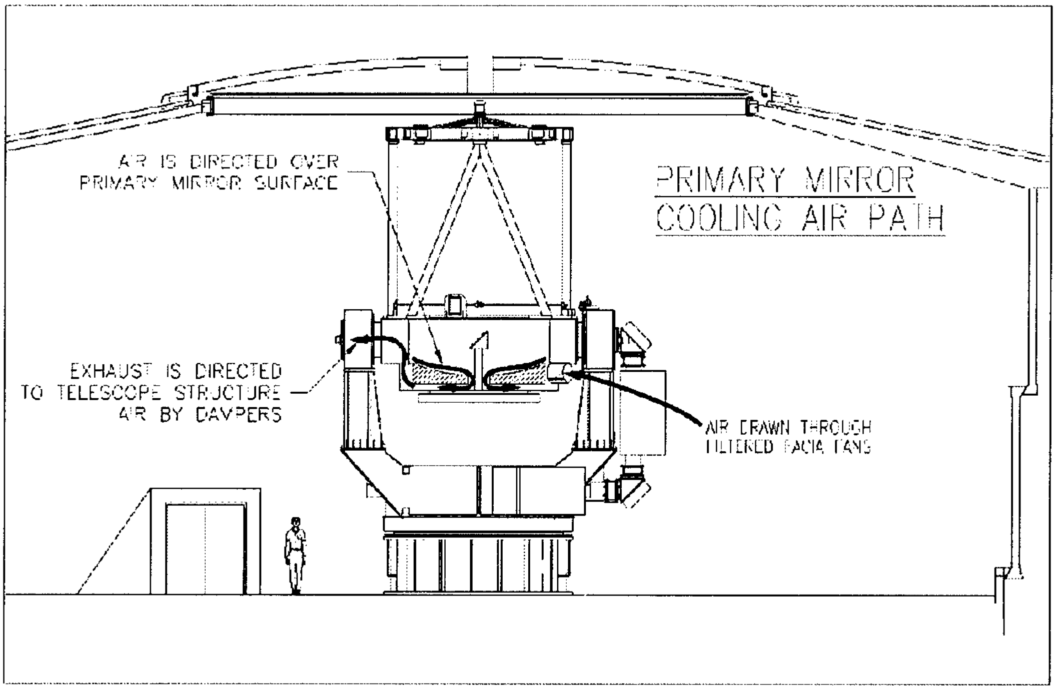

Figure 2. This figure illustrates the air path of the primary flushing system.

experiments have shown that these sorts of systems mitigate any temperature differences between the mirror and the ambient air[3].[4]

3. EXPERIMENTS

The main cause of image distortion is turbulence caused by temperature differences. Mirror seeing is caused by temperature differences between the mirror and the ambient air. Dome seeing is caused by temperature differences between the dome air and the outside air. The AEOS mirror temperature is computed from the average of the eight thermocouples mounted on the back of the primary mirror. The air temperature in the dome is recorded by a temperature sensor mounted near the southwest wall of the dome. The outside air temperature is recorded from the weather station mounted on the main observatory building - during the first portion of this year the other two weather stations were inoperable. The mirror temperature was plotted against the dome air temperature and is shown in Fig. 3. The temperature data is from 1 January 2002 through 11 March 2002. This period was before the mirror purge system was upgraded. After the upgrade some of the outside temperature data was corrupted. The data is filtered by the dome status, so that only temperature data while the dome is retracted is used. This eliminates daytime temperature measurements.

On average the dome air temperature appears to be warmer than the mirror temperature by several degrees. The outside air temperature is plotted against the dome air temperature in Fig. 4. Again the dome air temperature is higher than the ambient air temperature. The spike of outside temperatures that correspond to the dome temperatures of 45 F are anomalous. The outside temperature sensor experienced a malfunction at that time. One explanation of this is that the temperature prediction algorithm needs to be improved; as mentioned above we are installing new barometers to do this. A better way is to determine the accuracy of the temperature prediction algorithm is to plot a histogram of the difference between the predicted temperature and the actual temperature. Preparation of such a plot is under way.

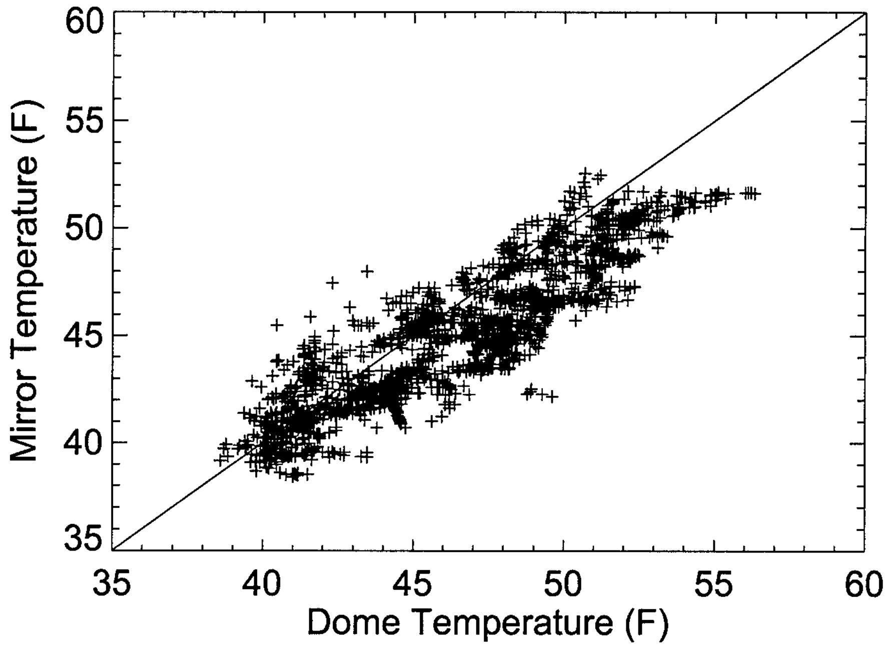

Figure 3. The dome air temperatures are plotted against the average mirror temperature. A line with unity slope is overplotted. The dome air temperature appears to be warmer than the mirror.

Another explanation is that the dome temperature sensor is biased. The sensor is located near the southwest wall, which is heated by the setting sun, this may increase the sensor readings, without actually increasing the air temperature near the telescope. Further investigation needs to be done to determine if this is the cause or something else is.

A series of experiments is planned to determine the efficacy of the various telescope air handlers. The basic idea behind all the of experiments is that we will turn various systems on and off and measure the seeing. Our metric for determining if the seeing improved was Fried's parameter (r_0). It would be best to isolate the dome/mirror seeing from the atmospheric seeing, but no easy way presented itself. By using an external measurement of Fried's parameter, we can change things at AEOS and then by looking at the external measurement, we can determine if the resulting change was caused by the atmosphere or the thermal conditioning.

The University of Hawaii operates the Day Night Seeing Monitor (DNSM) on Haleakala[8] and provides such an external measurement. The system measures r_0 using the differential image motion monitor technique. The DNSM is located approximately 100 feet to the southeast of the AEOS telescope. To determine if the measured r_0 values are representative of the r_0 value seen at AEOS, on 2002 June 5 at 5:00 UT, we recorded simultaneous data with the AEOS adaptive optics (AO) system. Data were recorded continually for the duration of the experiment as both systems observed the same stars. This produced 66 frames per minute. The exposure time was half a second, and the data were taken without AO or tip/tilt correction. To analyze the data, the 66 frames from each minute were co-added. The full-width-half-maximum (FWHM) of the combined image was measured and the r_0 was calculated from,

$$r_0 = 0.98 \frac{\lambda}{FWHM}, \tag{1}$$

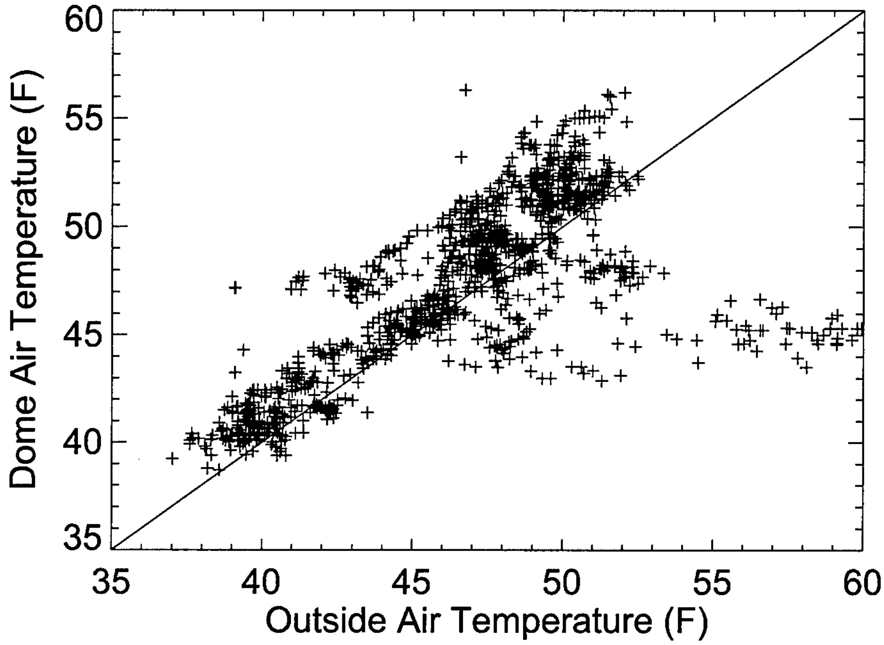

Figure 4. The outside air temperature is plotted against the dome air temperature. A line with unity slope is overplotted. The dome air temperature appears to be warmer than the outside temperature.

where λ is the wavelength of light.[9] The AEOS measurements were corrected to zenith and 500nm. The DNSM data is corrected to 500nm but not to zenith. Both data sets are very noisy; to make a meaningful comparison, the data sets were smoothed with a boxcar average with a window width of 11 data points. Some of the 'noise' in the data is real variations in the atmosphere, this can be seen as sometimes image quality improves dramatically for a few images. In the experiments, long data sets will be used to hopefully average out these variations. After smoothing, the two data sets show similar behavior, but not exactly the same. Both data sets show a dip around 6:00 UT. The slope of the graphs appear identical after 6:15 UT, though there is an offset between the data sets. The data sets are close enough that it was judged feasible to be used for further experimentation.

On 16 June 2002 UT, we again measured Fried's parameter simultaneously with AEOS and the DNSM. The procedure was the same except that exposure time was increased to one second, because a different star was being observed and a longer exposure time was required to get an image with a high signal-to-noise ratio. For the first two hours of the experiment, nothing was changed, but at 9:15 UT, the coudé tube fan was turned on. It was left on for 15 minutes, then turned off for 15 minutes. The process was repeated at 9:45 UT. The process would have continued for several more hours, but the telescope was engulfed by a cloud bank at 10:20 UT and stayed that way for the rest of the night. The data are shown in Fig 6. The gap in the AEOS data between 8:00 UT and 9:00 UT was because the telescope was temporarily used for another observation.

The first few hours of the data with no adjustments to the coudé fan, were to allow a second comparison between the DNSM and AEOS results. The agreement is not very good, until 8:00 UT. Between 8:00 UT and 10:00 UT, the agreement appears to be fairly good. Though there is the gap in the data, where the DNSM results spike up. It would have been interesting to see if the AEOS data followed the DNSM data.

Looking at the AEOS data, the coudé fan seems to have no effect on the data. The coudé room was had

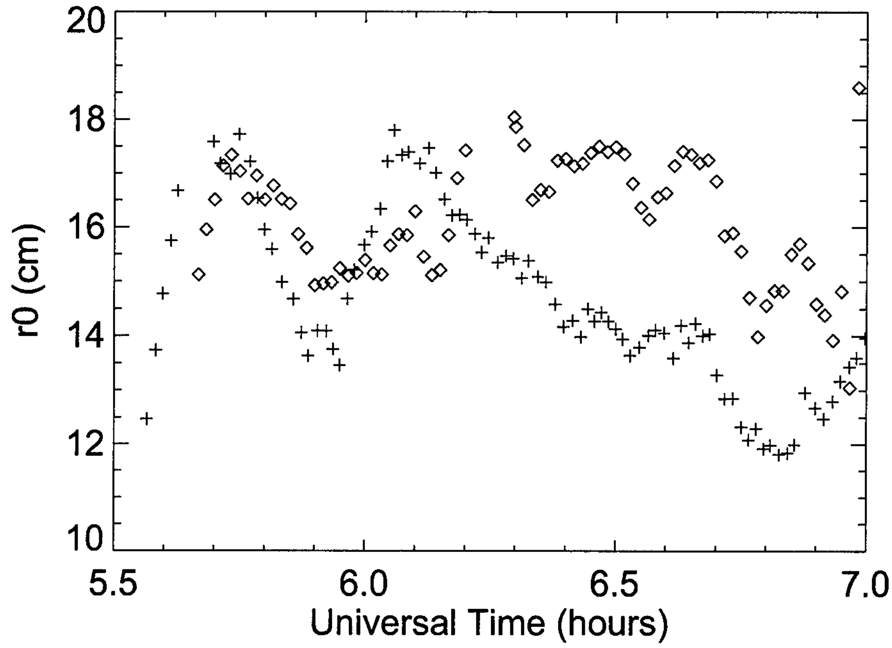

Figure 5. The AEOS measured r_0 (diamonds) are plotted against those from the DNSM (pluses). Both data sets were smoothed with a boxcar average.

a temperature of 62.5 degrees Fahrenheit. At the start of the observations, the reported mirror temperature was 48.2 F, the outside air temperature was 48.7 F and the dome temperature was 49.8. These are cold enough that it would see that there would be thermal currents in the coudé tube. It is possible that these currents are not disrupting the image or that the test is insensitive to the changes. Another data set that is hopefully unhindered by fog is planned and will be undertaken soon.

4. CONCLUSION

The thermal conditioning experiments are just getting under way. The coudé fan does not appear to have any effect on seeing, though the data is very limited. The primary flushing system is the system that we have the highest hope for. Similar systems have been shown to have a beneficial effect in the laboratory. Experimentation with this system will wait until the other systems have been explored.

ACKNOWLEDGMENTS

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REFERENCES

1. L. C. Roberts, Jr., and C. R. Neyman, "Characterization of the AEOS adaptive optics system," *Submitted to Pub. Astro. Society of the Pacific* , 2002.

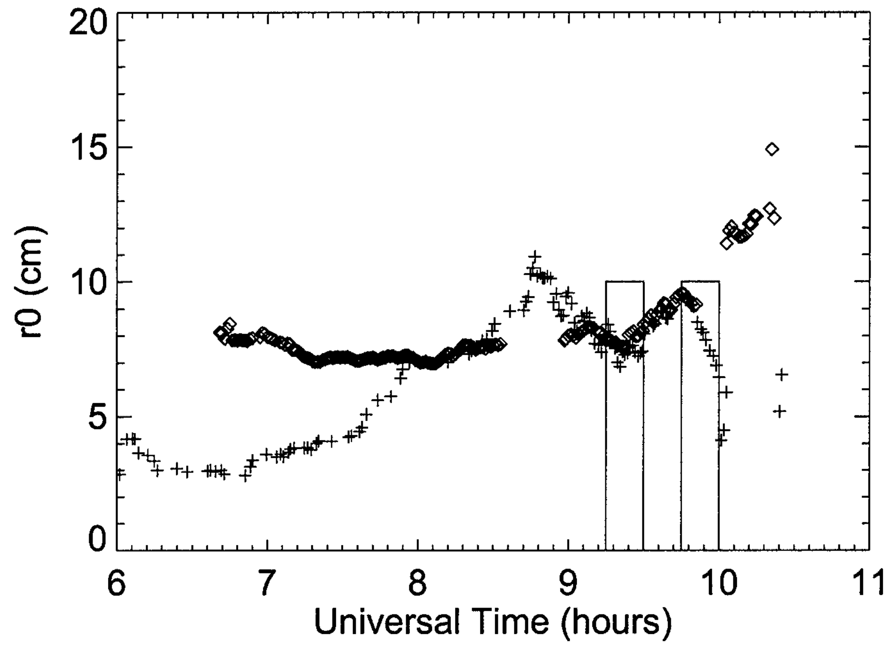

Figure 6. The AEOS measured r_0 (diamonds) are plotted against those from the DNSM (pluses). Both data sets were smoothed with a boxcar average. The solid line indicates when the coudé fan is engaged. The line is equal to 10 when the fan is on.

2. M. Skinner, A. Sylva, P. Figgis, D. Chesser, R. A. Brem, and A. Angara, "AMOS site atmospheric sensor improvements and sensor data fusion," in *2001 AMOS Technical Conference*, P. Kervin, L. Bragg, and S. Ryan, eds., pp. 80–87, 2001.
3. C. Lowne, "An investigation of the effects of mirror temperature upon telescope seeing," *Mon. Not. R. Astron. Soc.* **188**, pp. 249–259, 1979.
4. M. Iye, T. Noguchi, Y. Torii, , Y. Mikami, and H. Ando, "Evaluation of seeeing on a 62-cm mirror," *Pub. Astro. Society of the Pacific* **103**, pp. 712–722, 1991.
5. R. Racine, D. Salmon, D. Cowley, and J. Sovka, "Mirror, dome and natural seeing at CFHT," *Pub. Astro. Society of the Pacific* **103**, pp. 1020–1032, 1991.
6. M. Bridgeland and C. Jenkins, "Measurements of mirror seeeing in the laboratory and at the telescope," *Mon. Not. R. Astron. Soc.* **287**, pp. 87–109, 1997.
7. W. C. Marlow, "AEOS primary mirror temperture pre-conditioning," in *2001 AMOS Technical Conference*, P. Kervin, L. Bragg, and S. Ryan, eds., pp. 54–68, 2001.
8. M. Waterson, "Private communication," 2002.
9. M. Sarazin and F. Roddier, "The ESO differential image motion monitor," *Astron. Astrophys.* **227**, pp. 294–300, 1990.